WEB-BASED DISCUSSION
OF
LOW SWIRL COMBUSTION

FINAL LETTER REPORT

Prepared for

Office of Clean Power Systems
US Department of Energy

Prepared By

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Report Contents

1. Overview

On Wednesday, November 8, 2006 from 10 AM to Noon, PST, Lawrence Berkeley National Laboratories (LBL), in conjunction with the Office of Clean Power Systems of the US Department of Energy, and the Electric Power Research Institute (EPRI) presented a Web-based discussion of Low Swirl Combustion. The discussion featured a presentation by Dr. Robert Cheng, of LBL, who presented a summary of his work on the development of Low Swirl Combustion (LSC) technology. The objective of this web-based discussion was to provide researchers, vendors, and users of gas turbine equipment with an opportunity to learn about these R&D efforts and discuss them in an open forum with other interested parties. Participants were able to view Dr, Cheng's slides and listen to his presentation through their own remote computer facilities.

Invitations (see Section 5a) were sent by EPRI to almost 2000 individuals that were identified by DOE and EPRI as likely to have some interest in Low Swirl Combustion. Thirty-six individuals (See section 5b) representing desired elements of the target audience participated, as well as other individuals, at the locations shared with those who registered as participants in the web-based discussion. Additional participation has occurred through access to a recording of the webcast that has been posted on a publicly accessible EPRI-website.

Leonard Angello of EPRI opened the discussion with a brief summary of the EPRI Assessment Study of Ultra-Low NOx IGCC Combustors (see Section 5ci). LSC combustion is one of several approaches that EPRI is analyzing. Dr. Cheng then presented his material (see Section 5cii). Highlights of that part of the presentation covering the Status of Low Swirl Burner technology are presented in Section 2. Dr. Cheng's conclusions about LSC are presented in Section 3. A summary of the proposed R&D needed to support an assessment of the applicability of LSC to hydrogen fired gas turbines is presented in Section 4.

Access to the audio and visual presentation material has been archived and is available to interested individuals on the web at:
http://my.epri.com/portal/server.pt?Highlight_id=discussion_of_low_swirl_combustion_for_igcc_gas_turbine_applications__nov_06__da_350294.html

Author's Comments

On the basis of the material presented and audience reaction, it appears that LSC offers a very promising approach for near-term application in new natural gas-fueled gas turbines and combined cycles as an alternative to current complex and high maintenance Low-NOx combustors and post-combustion SCR systems. It would have even greater potential if "drop-in" modules were developed so that existing operating units could be modified to meet newly imposed NOx emission reduction requirements without the addition of SCR systems.

The data on syngas are not very extensive, but indicate that results on syngas would be very close to results that were obtained in laboratory experiments on diluted natural gas. Combustion tests in manufacturers' test facilities are required to qualify the use of LSC for consideration in the fleet of combined cycles installed in the next round of IGCC plants that are being planned. If this technology could meet its ultra-low NOx potential on syngas, it would reduce the cost of IGCC plants significantly and improve their environmental performance.

At this time, the situation relative to the use of LSC with hydrogen is inconclusive. A significant amount of R&D work is required to support consideration of this technology for use in IGCC plants that will fuel their gas turbines with hydrogen..

2. Status of Low Swirl Burner Technology

Background Information on LSC Technology

LSC is a dry-low NO_x technology conceived at LBL. It is currently being developed for application to 5-7 MW industrial gas turbines fueled with natural gas to achieve ultra-low emission targets of <5 ppm NO_x (at 15% oxygen) and <10 ppm CO without the use of post-combustion control systems such as SCR. A logical extension of the current program is the adaptation for hydrogen-rich gaseous fuels including coal-derived syngas and 90+% pure hydrogen and scale-up to the sizes of large utility gas turbines, ultimately meeting the long-range DOE goal of 2 ppm NO_x emissions (at 15% oxygen) from hydrogen-fired turbines at 2500-2600F turbine firing temperatures.

The LSC principle is fundamentally different than the high-swirl DLN concept where toroidal vortices with strong recirculation and intense shear turbulence are generated to hold and continuously ignite the turbulent premixed flames. LSC exploits the characteristic wave-like properties of premixed combustion and enables premixed turbulent flames to freely propagate in a divergent flow at swirl intensities well below the critical vortex breakdown threshold. With LSC, turbines will have greater flexibility in their operations than is achievable by current technology.

Laboratory experiments are being conducted currently on hydrogen fuel-specific issues, and discussions are underway with gas turbine manufacturers to define the specifications and operating conditions of the hydrogen low-swirl injector. Further background information on LSC is available at **http://eetd.lbl.gov/aet/combustion/LSC-Info/**

Comparison of Low and High Swirl Combustion for Flame Stabilization (see slide 23)

	Low Swirl	High Swirl
Principle	Flame propagates freely at its turbulent flame speed	Vortex traps hot products for continuous ignition of fresh mixtures
Approach	Generation of divergent flow with no recirculation	Generation of tight recirculation zone
Flame/turbulence interaction	Flame developing in isotropic turbulence with low shear stresses is less prone to fragmentation	Flame developing in high shear region leads to flame fragmentation and occasional detachment
Instability	No distinct characteristic frequency due to absence of recirculation	Characteristic frequencies associated with recirculating vortex

Natural Gas

- Low Swirl Combustors are now producing 4-7 ppm NOx @3% O2 in commercial Maxon industrial burners fueled with natural gas
    - M-PAKT burners (0.5 – 3.5 MMBtu/hr) available since 9/03 (see slide 29)
    - OPTIMA SLS gas/liquid dual fuel burners (12-50 MMBtu/hr) introduced in 2006 (see slides 29)
- Scaling rules have been established and validated for industrial burners and gas turbine injectors fueled with natural gas (see slide 34)
- Low Swirl Combustors are now producing NOx levels of <2.5 ppm@15% O2 in tests in a natural gas-fired 7.7 MW Solar Taurus 70 engine equipped with 12 annular injectors (see slide 39, 47 and 51)
- Designs are being developed for "drop-in" replacement injectors for the Solar Taurus 70 engine (see slide 44)
- Analytical means to quantify flame/flow relationship have been validated (see slide 76)
- Flashback and flame positions are predictable from analytical equation (see slide 77)
- NOx emissions show log-linear dependence on flame temperature (see slide 81)

Syngas

- Combustion properties of syngas flames are similar to those of low Btu hydrocarbon fuels (see slide 85)

Hydrogen

- Distinct characteristics of hydrogen flames due to high diffusivity and reactivity (see slide 85)

    - Premixed turbulent flames not well understood
    - Demonstration needed of the feasibility of LSC for hydrogen flames
- Short Auto-Ignition Time compared to hydrocarbons (see slide 85)
- Dominant flame flow coupling processes for hydrogen and hydrocarbon flames are the same (see slide 91)
- Higher hydrogen flame speed correlation can be accommodated by a small reduction of the swirl number (see slide 91)

3. Conclusions

- LSC is a cost-effective and robust enabling ultra-low NOx emission technology for natural gas turbines and shows very good promise for fuel-flexible turbines utilizing blended hydrocarbon fuels
- The principle of LSC is described by a top level model that can be used to guide its scale-up for large utility turbines
- LSC shows good promise for large turbines operating on natural gas and other hydrocarbons
- Development for syngas and hydrogen turbines requires empirical inputs as well as fundamental combustion properties of hydrogen flames to guide the adaptation (see slide 100)

4. Identification of Key Research Areas for Additional R&D to Support Adaptation of LSC for Hydrogen Fired Turbines

<u>Fundamental Issues</u>

- Ignition delay (see slide 93)
    - To prevent premature ignition, the residence time of hydrogen reactants within the combustor cannot be longer than the auto-ignition delay time (see slide 95)
- Turbulent flame speed correlation (see slide 93)
    - Hydrogen ignition delay data is not available at relevant gas turbine operating temperatures and pressures (see slide 95)
- Unknown properties of hydrogen flames at high pressures (see slide 93)
    - Reaction rate - Hydrogen flames are inherently unstable due to preferential diffusion (see slide 93 and 97)
    - Flame volume - Hydrogen flames may need larger combustion chambers (see slide 93 and 97)
    - Reaction zone structures of turbulent hydrogen flames are different than those of hydrocarbon flames (see slide 97)
    - Heat release models for hydrocarbon flames are not suitable for hydrogen flames (see slide 97)
- Predict emissions at relevant conditions (see slide 93)
- Instability aspects of Low Swirl Injectors (see slide 93)

- Modeling and simulation (see slide 93)
- Flowfield emission coupling (see slide 93)

Engineering Issues

- Scaling to larger sizes (see slide 93)
- Fuel injection, premixer, and nozzle design (see slide 93)
- Verify operation at higher temperature and pressure (see slide 93)
- Optimize for fuel flame properties – syngas vs. hydrogen (see slide 93)
- LSI/Combustor layout (see slide 93)
- Integration with other components (see slide 93)
- Operation and controls with emphasis on the invisibility of hydrogen flames (see slide 93)

5. Appendices

a. Invitation

LAWRENCE BERKELEY NATIONAL LABORATORY (LBL)
in conjunction with the
DEPARTMENT OF ENERGY (DOE) OFFICE OF CLEAN POWER SYSTEMS
and
ELECTRIC POWER RESEARCH INSTITUTE (EPRI)

invite your participation in a
WEB-BASED DISCUSSION OF LOW SWIRL COMBUSTION *
on
Wednesday, November 8, 2006
at
10:00 AM to Noon, PST

*** "This webcast and the audio will be recorded, and your participation provides consent to that recording." Webcast seating is limited to 65 participants, available on a first-come, first-serve basis. The webcast with audio will be posted after the meeting on the Live Meeting website.**

Webcast Topic

This web-based discussion will feature a presentation by Dr. Robert Cheng, Lawrence Berkeley National Laboratory, that describes his work on the development of Low Swirl Combustion (LSC) technology. The objective of this web-based discussion is to provide researchers, vendors, and users of gas turbine equipment with an opportunity to learn about these R&D efforts and discuss them in an open forum with other interested parties.

Background Information on LSC Technology
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Webcast Participation Information

Live Meeting First Time Users

If this is your first Live Meeting, you should install the Windows-based Meeting console before the meeting starts and check your system to see if it is compatible with Live Meeting. **Click here** to install the Live Meeting 2005 Windows-based Meeting Console before your meeting.

Audio Call in Number

Toll free: (888) 564-3287; Participant code: 8224

Live Meeting Webcast Site Address

https://www.livemeeting.com/cc/epripremier/join?id=NWRSZ8&role=attend&pw=m%2F6Np2q%7Ep

Webcast Agenda

Time	Subject
10:00 AM	Introduction of **Dr. Robert Cheng**
10:05 AM	Introduction to **Low Swirl Combustion** Technology, including a history of Low Swirl Combustion development and applications, the theoretical basis for recent successes with LSC combustion and review of LSC models.
10:25 AM	Q&A on **LSC Technology**.
10:35 AM	Presentation of **Data** summarizing lab experience, the Maxon burner industrial experience and if possible the Solar Turbine experience and discussion of scale-up approaches.
10:55 AM	Q&A on **Data**
11:00 AM	**Potential Applications** of LSC in large scale turbines for natural gas, syngas, and hydrogen fuels.
11:15 AM	Q&A on **Potential Applications**
11:20 AM	**Scale-up Issues and Future Challenges** that may arise in successful scale-up to larger machines.
11:30 AM	Q&A related to **Scale-up Issues and Future Challenges**
11:35 AM	**Needed R&D** to overcome potential Issues and challenges
11:50 AM	Q&A on **Needed R&D**
11:55 AM	Wrap-up

Noon	Adjourn

The Webcast presentation material and a list of Frequently Asked Questions and Answers on LSC will be posted at http://eetd.lbl.gov/aet/combustion/LSC-Info/ on or before November 1, 2006.

b. Participants

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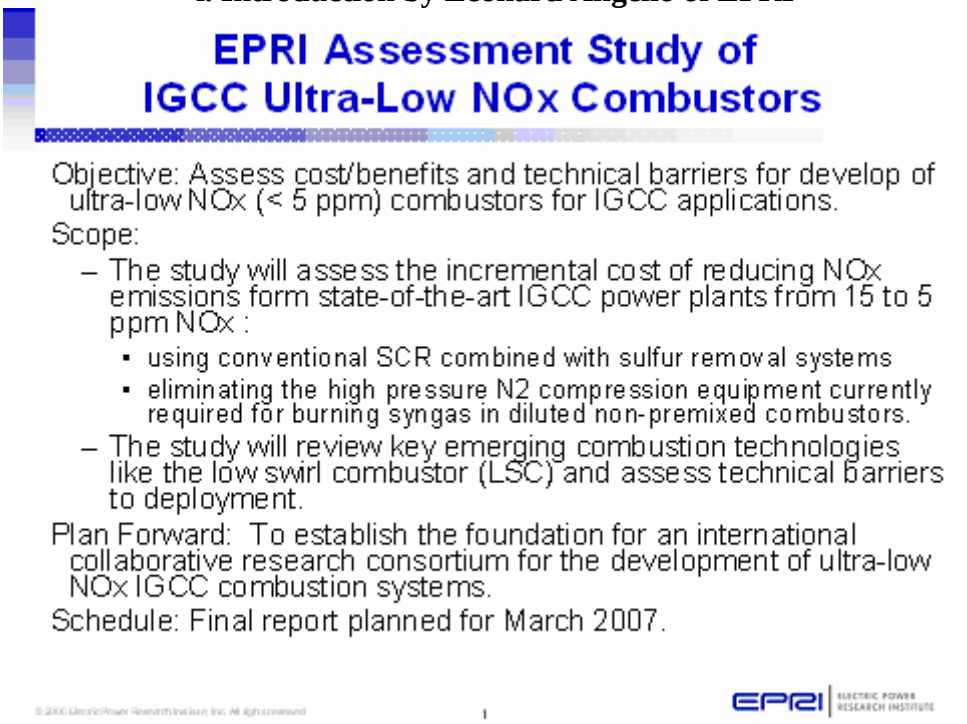
c. Presentation materials

i. Introduction by Leonard Angello of EPRI



ii. Dr. Robert Cheng's Presentation

WEB-BASED DISCUSSION OF LOW SWIRL COMBUSTION

If you missed or wish to re-view the recent November 8, 2006 webcast entitled *'Discussion of Low Swirl Combustion',* it is now available for viewing at EPRI.com. You may view directly via the link: http://my.epri.com/portal/server.pt?Highlight_id=discussion_of_low_swirl_combustion_for_igcc_gas_turbine_applications__nov_06__da_350294.html

Description:

In response to the challenges of burning syngas in IGCC gas turbines, EPRI has initiated a new study to assess the cost/benefits associated with the development of ultra-low NOx combustor technologies to serve the IGCC power generation market. The purpose of this study is to investigate the cost, benefits, and technical barriers associated with the development of ultra-low emission (< 5 ppm) NOx combustion systems for IGCC applications, and compare those to the option of achieving <5 ppm NOx via the use of deeper sulfur removal and the addition of an SCR. The study reviews emerging combustion technologies such as Low Swirl Combustion (LSC) to enable the development of advanced gas turbines with of ultra-low (< 5 ppm) NOx combustion systems that will operate reliably and efficiently when fueled with coal-derived syngas.

For more information: Contact Leonard Angello at langllo@epri.com, (650) 855-7939.